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# Attitude control schemes for the first recovery mission of India☆

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**Abstract**

This paper describes the attitude control schemes for the various phases such as acquisition, on-orbit, orbit maneuver, de-boost maneuvers and coast phases of the India's first recovery mission Space Capsule Recovery Experiment-I (SRE-1). During the on-orbit phase, the SRE was configured to point the negative roll axis to Sun. The attitude referencing of SRE-1 was based on dry tuned gyros with updates from the attitude determined using on-board Sun sensors and magnetometer. For attitude acquisition, attitude maneuvers and for providing the velocity corrections for de-orbiting operations; a set of eight thrusters grouped in functionally redundant blocks were used. The control scheme with thrusters was based on proportional derivative controller with a modulator. In order to ensure micro-gravity environment during the on-orbit payload operations a linear quadratic regulator (LQR) based control scheme was designed to drive an orthogonal configuration of magnetic torquers which in turn produced three-axis control torque with the interaction of Earth's magnetic field. Proportional derivative control scheme with modulator was designed to track the steering commands during the velocity reduction as well as during the coasting phase of the de-orbiting operations. A novel thruster failure detection, isolation and reconfiguration scheme implemented on-board for the de-orbiting phase is also discussed in this paper.


## 1. Introduction

Space Capsule Recovery Experiment (SRE-1) capsule weighing 555 kg was launched onboard PSLV C-7 on January 10, 2007 and was recovered on January 22, 2007. The objective of the mission was to conduct microgravity experiment, de-orbit and recover it in Indian sea waters, off the coast of Sriharikota. The control system for SRE-1 was designed to meet the attitude control requirements during the various phases of the mission such as Sun acquisition, Sun pointing, De-boost phases, etc. The total mission profile of SRE-1 is given in Fig. 1.

The attitude control system was designed to ensure negative roll axis pointing to Sun during the on-orbit phase and track the guidance command during the de-orbiting operations. The attitude reference was derived from two orthogonally mounted dry tuned gyros (DTG) which give the yaw, roll and pitch attitude with roll having redundancy.

Attitude derived from DTGs were updated using a high accuracy Sun sensor called Fine Analog Sun Sensor (FASS) and the attitude derived from three-axis magnetometer. The Sun vector computed in the target frame along with the measured Sun vector and the

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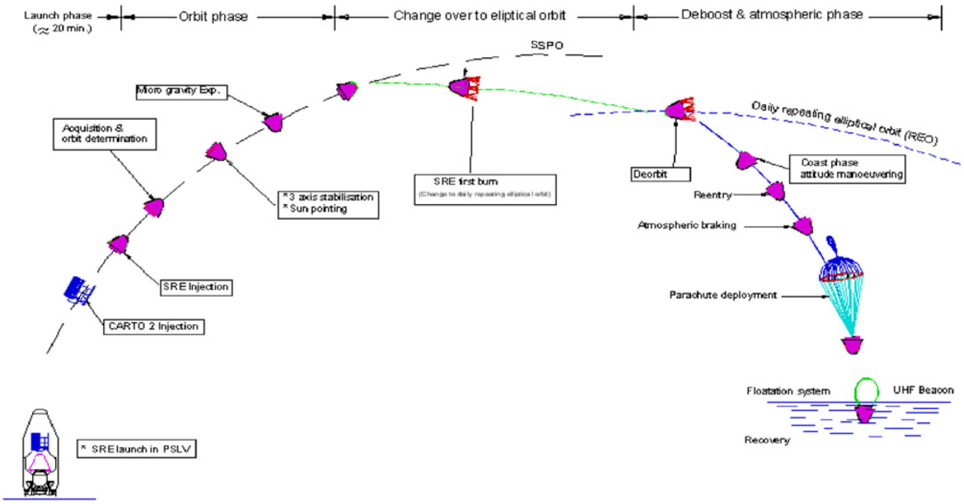



Fig. 1. SRE-1 mission sequence profile.

geo-magnetic field vector were used for obtaining the absolute attitude information.

There were two different types of actuators for the attitude control purposes. First one is a set of eight thrusters mounted in such a manner that, it provides three-axis attitude control capability with redundancy and the capability to impart velocity for de-orbiting purpose. The second set of actuator is magnetic torquers mounted orthogonally to provide control torque about all the three axes.

The basic control algorithm for the thruster control modes uses a proportional derivative controller with a modulator [1]. Depending on the modulators outputs of all the three axes, the required thrusters will be selected for firing using a selection table. During the thrusting phase for reducing the orbital height, the thrusters will be operating in the off-modulation mode to cater to both attitude control and imparting thrust in the required direction. During the de-boost phases closed loop guidance and control scheme was used in which the guidance attitude commands were compared with the actual attitude to derive the error and correct the error by off-modulating the required thrusters. A linear quadratic regulator (LQR) based controller was designed to control the attitude with magnetic torquers [2].

Also, in order to reduce the off-modulation during the thrusting phase under a thruster failure, a novel thruster failure detection and isolation scheme was evolved for SRE-1 [3]. The same scheme was extended to identify and isolate a thruster which is firing continuously during the coasting phase where continuous firing is not called for. The failure detection in both the cases was feasible due to the unique torque directions from each of the eight thrusters.

The following sections will describe the configuration and algorithms used in SRE-1 for the different phases of the mission. Typical simulations results as well as the performance obtained on-board [4] are discussed.

## 2. Sensors and actuator configuration

As already mentioned, attitude reference was derived from DTG and the attitude update was carried out using the attitude derived from the FASS and magnetometers. For attitude acquisition a coarse Sun sensor called 4 Pie Sun sensor was used.

In SRE-1, for attitude and orbit control, the spacecraft is provided with eight 22N thrusters grouped into two blocks. This configuration is arrived at to have block level redundancy. The two blocks can be selected independently and each thruster can be enabled/disabled for firing. During de-boost phase all the eight thrusters (both the blocks) will be used. Either Blocks I or II will be selected during other phases. The thruster configuration along with the axes definition is given in Fig. 2.

In order to ensure microgravity during the experiments, three magnetic torquers mounted orthogonally were used as the actuators. As a backup thrusters were also used for attitude control but deviating the microgravity level. The various sensors and actuators used during different phases for controlling the module are given in Table 1.

## 3. Reference attitude for Sun pointing

The Sun pointing attitude requirement should ensure negative roll axis point towards Sun. Another requirement was that negative yaw direction should point

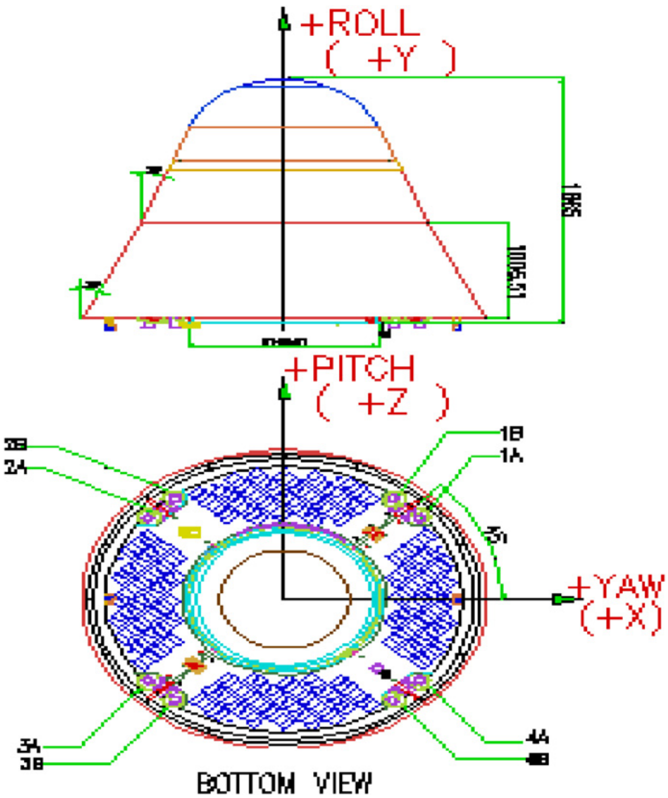



Fig. 2. SRE-1 thruster configuration.

Table 1
Sensors and actuators configuration for control systems.

| Phase | Sensor | Actuator |
|---|---|---|
| Sun acquisition | 4 Pie Sun Sensor<br>Fine Analog Sun Sensor<br>DTG | Thrusters |
| On-orbit phase | Magnetometer | Magnetic torquers/ Thrusters |
| | Fine Analog Sun Sensor<br>DTG | |
| Attitude manoeuvre | DTG | Thrusters |
| De-boost phase | DTG | Thrusters |
| Coast phase | DTG | Thrusters |

towards deep space during the on-orbit phase. In order to meet these requirements, Pitch axis is defined as the cross product of position vector and the Sun vector. The yaw axis is defined as cross product of roll axis and the pitch axis.

The geometry requires a varying roll rate during the on-orbit phase. The required geometry is ensured by computing the yaw, roll and pitch unit vectors in ECI from the position and Sun vector computation and using these unit vectors the target attitude for Sun pointing is computed.

## 4. Onboard SunMagAD

A new scheme of three-axis attitude determination was therefore proposed and realised for SRE using the data from Magnetometer and FASS which provide information on two vectors namely the geomagnetic field vector and Sun vector, respectively.

Software modules developed onboard includes: (i) model-based orbit propagation; (ii) $Q_{IO}$ and DCM for inertial frame transformation; (iii) $Q_{IS}$ and DCM for Sun frame transformation; (iv) orbit parameters computation; (v) magnetic field computation; (vi) reference vector computations; (vii) magnetometer data processing; (viii) FSS data processing; (ix) data normalization; and (x) discrete attitude determination. The onboard processing for reference field generation and the SunMagAD was designed to be available only when the Sun presence signal (SPS) is available from FASS of SRE.

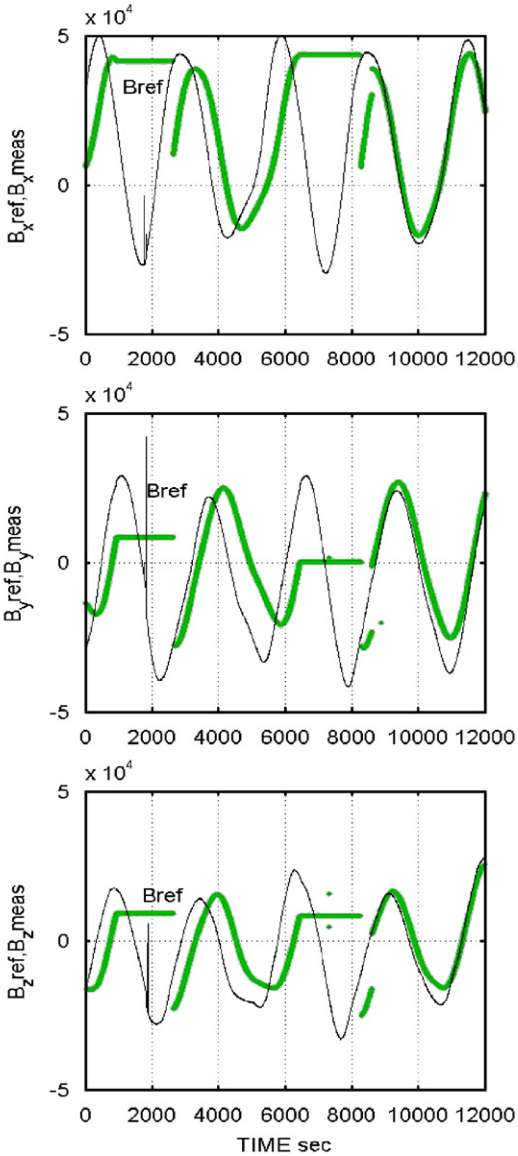



Fig. 3. Onboard ref and actual geomagnetic field components.

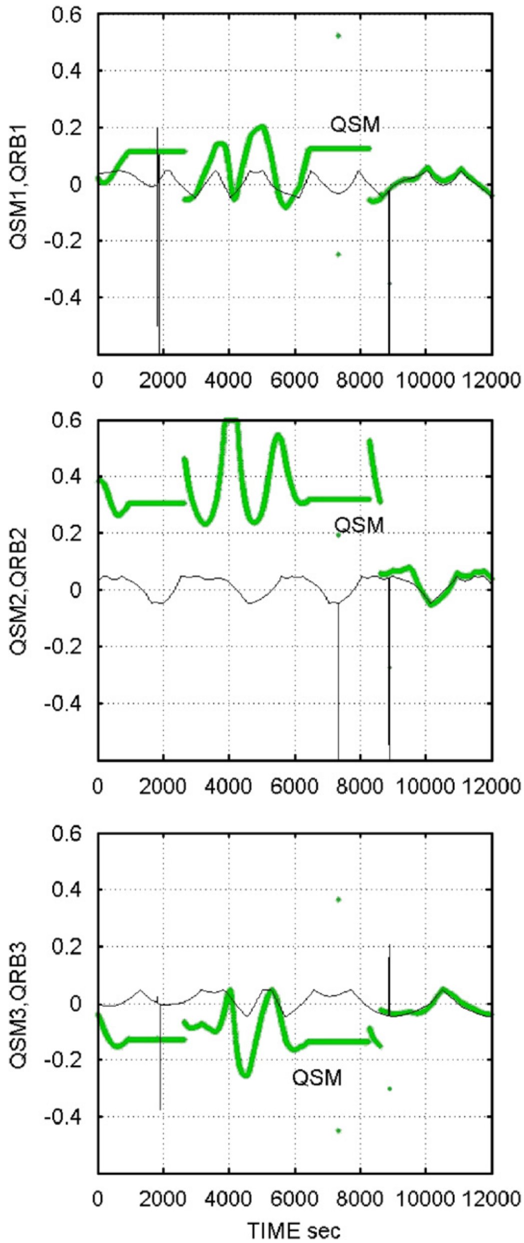



Fig. 4. Actual attitude (QRB) and SunmagAD results (QSM).

Fig. 3 shows the plots of geomagnetic field components measured by onboard magnetometer and the reference field generated by onboard geomagnetic field model. Since processing for SunMagAD is active only when FASS SPS is present, Bref, the reference field generation is flat during eclipse duration at around 2000 and 7000 s in these plots. The initial mismatch in onboard generated reference field gets corrected by end of 9000 s after uplink of orbit coefficients and residual magnetic field biases.

Fig. 4 shows the actual attitude of the spacecraft body w.r.t. the required reference (i.e. QRB) along with the three-axis attitude determined using SunMagAD. The convergence of SunMagAD results within 1° following the uplinks are self explanatory. Fig. 5 shows the measured pitch and yaw outputs from FASS. The third plot depicts the attitude determination errors (ADErr) from the SunMagAD w.r.t. to the expected attitude reference profile.

The flatness in the FSS plots at around 1500 s and later around 7500 s is due to eclipse duration when FASS

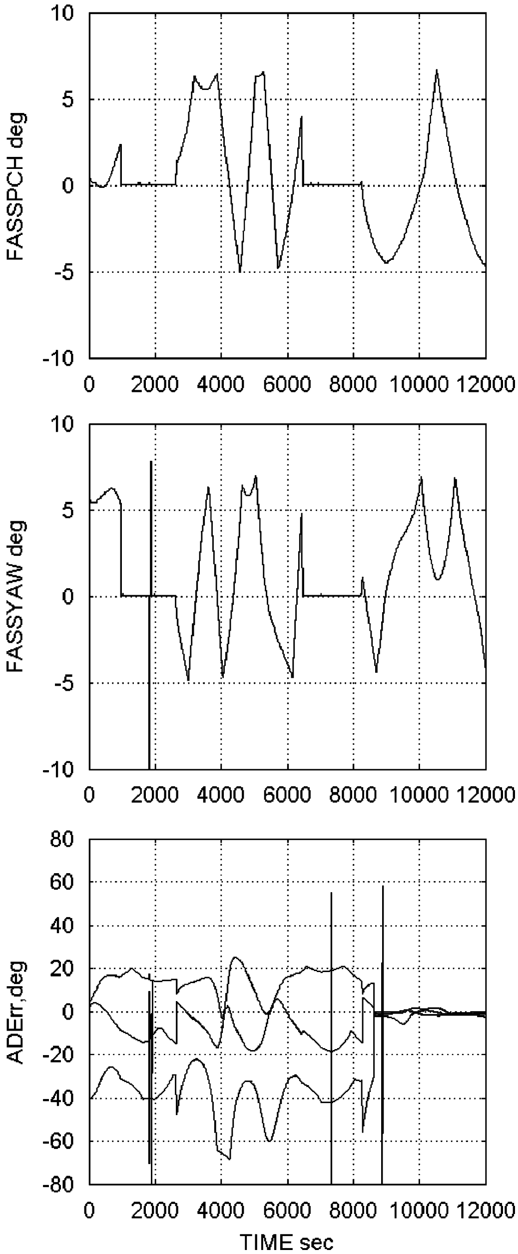



Fig. 5. FASS data and ADErr (QSM–QRB) from SunmagAD.

SPS is absent. During this time software processing for reference field and SunMagAD are not active. Due to small size of the spacecraft, the residual magnetism in SRE and its impact was more than what was expected from our experiences with bigger spacecrafts like INSAT and IRS. However, after the launch, effects due to residual bias was compensated to some extent and SunMagAD helped inertial pointing of SRE within a drift of not more than 0.1°/h which was also a factor that contributed to the successful re-entry and recovery of the mission.

## 5. Attitude propagation from gyro output

The attitude is represented as quaternion which is a four parameter representation of the spacecraft attitude. For three-axis attitude propagation with DTG measurements, the quaternion scheme has many well-known advantages like computational efficiency, linear equations and shortest path rotation during manoeuvre.

The quaternion $[Q_1\ Q_2\ Q_3\ Q_4]$ can be propagated after initializing the quaternion in Earth centred inertial reference (ECI) frame using the known absolute attitude derived. The quaternion propagation algorithm uses the three incremental angles from DTGs after drift rate compensation. Denoting these angles as $\Delta X$, $\Delta Y$, $\Delta Z$ for yaw, roll and pitch, respectively, the steps involved are as follows:

(a) *Computation of the incremental quaternion—$\Delta q$*: These are the intermediate quaternion parameters corresponding to the dynamics (body rates) of the spacecraft during the current propagation interval.

$$\Delta q_1 = \tfrac{1}{2}\Delta X * \mathrm{CDR}$$

(CDR is the conversion factor from degree to radian)

$$\Delta q_2 = \tfrac{1}{2}\Delta Y * \mathrm{CDR}$$

$$\Delta q_3 = \tfrac{1}{2}\Delta Z * \mathrm{CDR}$$

$$\Delta q_4 = 1 - \tfrac{1}{3}(\Delta q_1^2 + \Delta q_2^2 + \Delta q_3^2)$$

(b) *Propagation of the attitude quaternion*:

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{bmatrix}_{K+1} = \begin{bmatrix} \Delta q_4 & \Delta q_3 & -\Delta q_2 & \Delta q_1 \\ -\Delta q_3 & \Delta q_4 & \Delta q_1 & \Delta q_2 \\ \Delta q_2 & -\Delta q_1 & \Delta q_4 & \Delta q_3 \\ -\Delta q_1 & -\Delta q_2 & -\Delta q_3 & \Delta q_4 \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{bmatrix}_K$$

where $K$ and $K$+1 are the current and subsequent steps.

## 6. Attitude control schemes

### *6.1. Attitude control scheme for Sun pointing with thrusters*

#### *6.1.1. Inertial pointing*

SRE-1 was required to be pointed with negative roll axis pointing to Sun. The inertial target attitude for the same was computed from ground and uplinked.

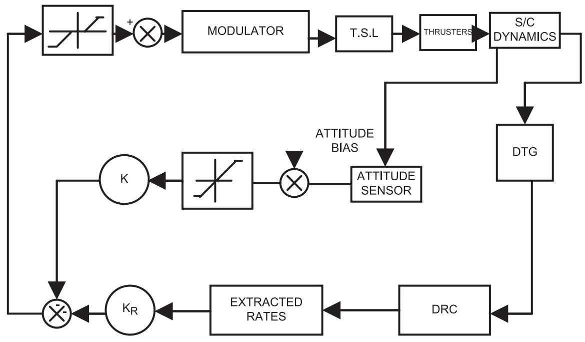



Fig. 6. Block schematic of a single axis thruster control scheme.

The spacecraft error quaternion with respect to body was computed as follows:

$$Q_{\mathrm{RB}} = Q_{\mathrm{IR}}^{-1} \Theta Q_{\mathrm{IB}}$$

where $Q_{\mathrm{RB}}$ is the error quaternion and $Q_{\mathrm{IR}}$ is the reference quaternion in inertial frame and $Q_{\mathrm{IB}}$ is the present body quaternion.

The attitude acquisition is achieved by feeding the error quaternion obtained and the rate derived from the DTG output to a proportional derivative controller. The output of the controller is passed to a modulator whose output is used for selecting the required thrusters. The basic block diagram of the control scheme is given in Fig. 6. The controller parameters are chosen such that the required pointing and the damping are ensured for each axis.

### *6.1.2. Sun pointing with roll rate*

The reference attitude was derived to ensure negative roll axis pointing to Sun and the negative yaw axis pointing to deep space as mentioned in Section 3. In this case also the attitude controller was same as the one mentioned in Section 6.1.1, except the error was derived from the reference attitude computed onboard.

## *6.2. Attitude control scheme with magnetic controller*

Design of the three-axis fully magnetic attitude control system is aimed at the development of the efficient, fully magnetic attitude controller that utilizes the gyro as sensor and the magnetic torquers as actuators. In the magnetic controller design, a number of challenges should be taken into account. Firstly, the system is under-actuated. Secondly, the dynamical system with the magnetic actuation is roughly a periodic one. Thirdly, the controller must be robust with respect to the satellite's moments and products of inertia. The under actuated nature of the system along with its approximate periodicity generates a challenging feedback controller design problem. The goal of this system is to achieve microgravity environment for the payloads of SRE. In order to cope up with all these challenges, a new three axis fully magnetic attitude controller based on a time varying, full state feedback LQR control law was designed for SRE on orbit phase control which requires roll axis Sun pointing.

Magnetic control is achieved by three mutually orthogonal coils whose dipoles are along principal axes of the body. The resulting torque is

$$T_{\mathrm{c}} = m \times B$$

where $B$ is the Earth's magnetic induction. Above equation states that $T_{\mathrm{c}}$ of the magnetic actuated satellite always lies perpendicular to the geomagnetic field vector $B$, which is a function of the orbital position of the spacecraft. Furthermore, a magnetic moment $m$ generated in the direction parallel to the local geomagnetic field has no influence on the satellite motion. This can be explained by the following equality

$$N_{\mathrm{ctrl}} = (m_{\mathrm{pa}} + m_{\perp}) \times B = m_{\perp} \times B$$

where $m_{\mathrm{pa}}$ is the component of the magnetic moment $m$, parallel to $B$, and $m_{\perp}$ is perpendicular to the local geomagnetic field.

The satellite considered here is modelled as rigid body in the Earth's gravitational field influenced by internal control torque by the magnetotorquers and external disturbance torques e.g. gravity gradient torque. Linearized attitude dynamics model is used in control design and in closed loop stability analysis. The control will be with respect to the Sun pointing reference frame mentioned in Section 3. The magnetic field in spacecraft coordinates is computed using IGRF model. The gravity gradient model computes the disturbance torque due to gravity gradient as a function of the spacecraft's position, attitude and inertia matrix. The nonlinear rigid body attitude dynamics model which includes kinematics and dynamic equations of motion is used for long period simulations (for a period of one full day).

A simple periodic LQR problem is to find:

$$u(t) \quad \text{for } 0 \leqslant t \leqslant T$$

To minimize:

$$J = \frac{1}{2}\int_0^T [x^{\mathrm{T}}(\tau)Qx(\tau) + u^{\mathrm{T}}(\tau)Ru(\tau)]\,\mathrm{d}\tau + \frac{1}{2}x^{\mathrm{T}}(T)P_{\mathrm{T}}x(T)$$

subject to:

$$\dot{x} = Ax + B_b(t)u; \quad x(0) \text{ given}$$

where $x$ is the state vector containing the attitude with respect to the Sun pointing reference frame and body rates, $Q$ and $R$ are constant weighting matrices, $P_T$ is the terminal state-weighting matrix, $B_b(t)$ is assumed to be exactly periodic.

It is well known that the solution to above problem can be expressed in the form of a feedback control law

$$u(t) = -R^{-1}B_b^T(t)P(t)x(t)$$

where $P(t)$ is the solution of a time-varying matrix Riccati equation. The true $B(t)$ is not exactly periodic. The only time-varying component of its gain is the matrix $B(t)$. $B(t)$ is constructed from magnetometer measurements.

To avoid onboard solving of Riccati equation, solution of Riccati equation is computed on ground based on time slice approach. This gain scheduler is stored onboard. There are two switch over logics, the first one is to transfer the control from thrusters to torquers once the rates are well within the defined limits. The second logic is to transfer the control from torquers to thrusters in case of large attitude error in one of the axes for a predefined duration which is implemented onboard.

In SRE-1, the roll axis Sun pointing requirement results in different attitude in inertial frame with respect to season/time of year. Extensive control simulations are carried out for different seasons using different combinations of initial conditions of attitude errors and rates. Robustness studies are also carried out by perturbing inertia parameters and also for different values of gyro drift values. In on-orbit control phase of SRE, pointing requirement is relaxed as the purpose is to create micro gravity environment for the pay loads. The control performance met the system requirement.

In the actual flight, it is demonstrated well that by using magnetic torquers alone the three axes attitude stabilization with relaxed pointing requirement can be done.

### 6.3. Attitude control scheme during the de-orbiting operations

In order to ensure accurate re-entry of the module, a navigation, guidance and control scheme was implemented for the SRE-1 flight. Position and velocity information from the navigation system was used in the guidance algorithm to derive the target quaternions during de-boost operations as well as during the coast phase till the re-entry point is achieved. Once the re-entry point is achieved the navigation, guidance and control were cut off and during the atmospheric region it was a ballistic flight.

During the de-boost and subsequent coast phase also the attitude controller was same as the one mentioned in Section 6.1.1, except the error was derived from the

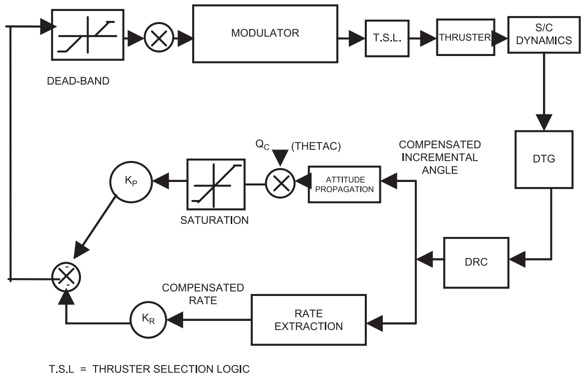



Fig. 7. Block schematic thruster control scheme during de-boost and the coasting phase.

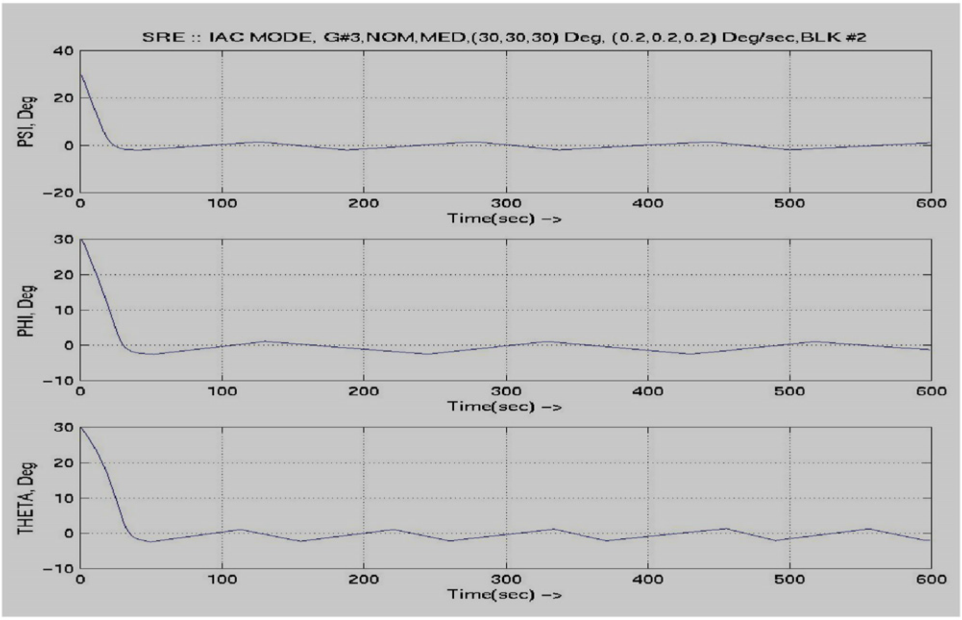
Table 2
Details of the error direction and corresponding actions for closed mode failure during off-modulation.

| Thrusters | Error direction during off-modulation | | | Thrusters to be put off for closed failure |
|---|---|---|---|---|
| | $Y$ | $R$ | $P$ | |
| 1A | + | + | − | 3B &1A |
| 1B | + | − | − | 3A &1B |
| 2A | + | − | + | 4B & 2A |
| 2B | + | + | + | 4A & 2B |
| 3A | − | + | + | 1B & 3A |
| 3B | − | − | + | 1A & 3B |
| 4A | − | − | − | 2B & 4A |
| 4B | − | + | − | 2A & 4B |

Table 3
Details of the error direction and corresponding actions for open mode failure during on modulation.

| Thrusters | Error direction during on-modulation | | | Thruster blocks to be put off for open failure |
|---|---|---|---|---|
| | $Y$ | $R$ | $P$ | |
| 1A | − | − | + | Blk1 |
| 1B | − | + | + | Blk2 |
| 2A | − | + | − | Blk1 |
| 2B | − | − | − | Blk2 |
| 3A | + | − | − | Blk1 |
| 3B | + | + | − | Blk2 |
| 4A | + | + | + | Blk1 |
| 4B | + | − | + | Blk2 |

a

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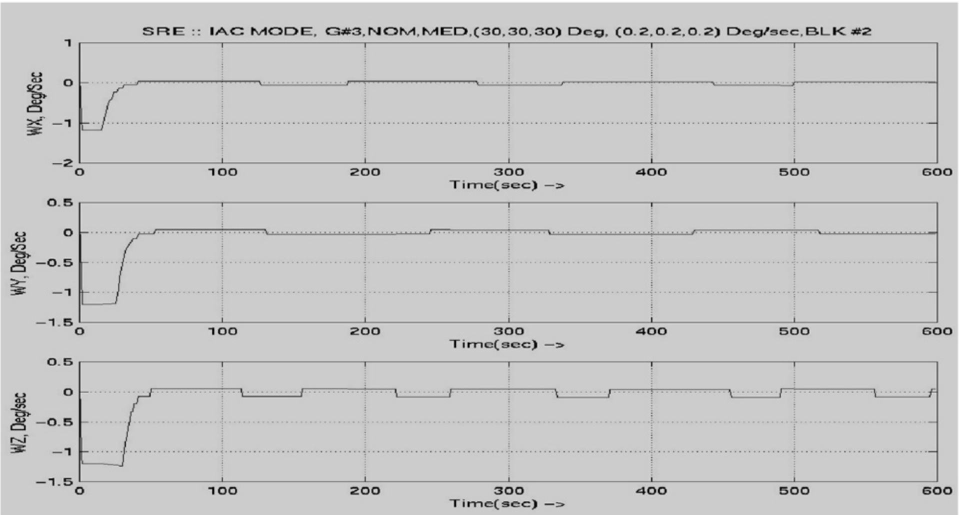


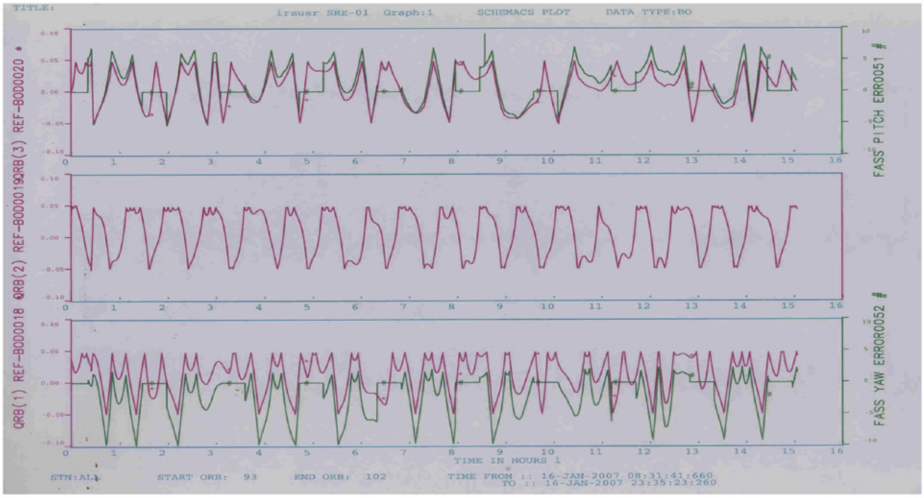

Fig. 8. (a) attitude convergence in acquisition mode; (b) rate convergence in acquisition mode; (c) attitude holding in thruster mode; (d) attitude rates in thruster mode; (e) attitude rates in thruster mode (with roll rate); (f) attitude with magnetic controller; (g) on orbit performance with magnetic controller; (h) rate profile predicted during de-boost phase; and (i) rate profile obtained during de-boost phase.

reference attitude was taken from the guidance output. Fig. 7 gives the block schematic of the control scheme during de-boost and coast phases. But, the controller parameters were designed such that the tracking error is within the acceptable limit. During the re-orientation phase also the guidance target computation was ensuring the negative yaw axis pointing to deep space. The controller parameters were designed such that, the error biases during the re-orientation phases were all within acceptable limits.

## 7. Thruster failure detection and isolation logic

For the SRE-1 Mission, 8 thrusters are planned to be used during the de-boost phase and for the orbit maneuvers. If one of the thrusters is failed to fire during

c

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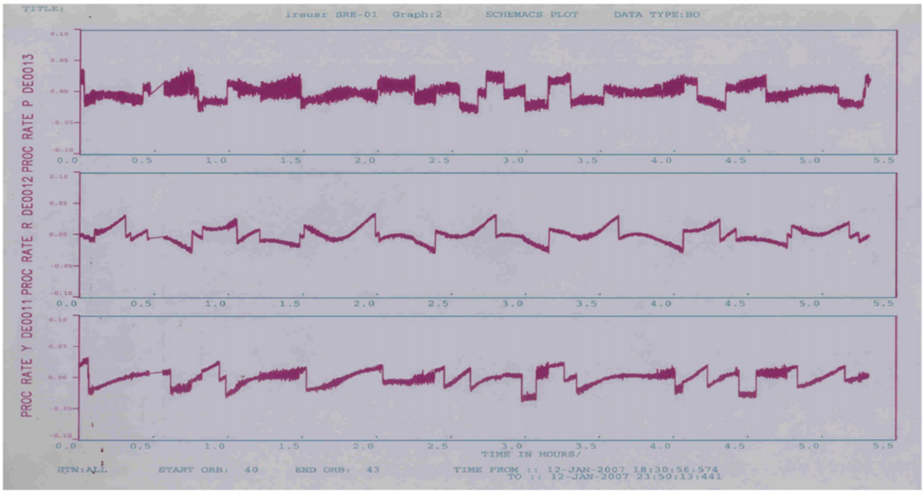


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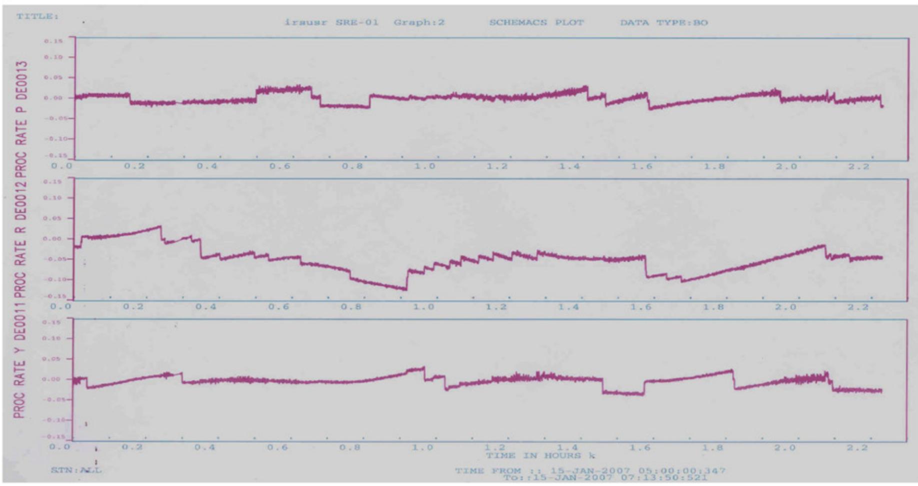



Fig. 8. (*continued*).

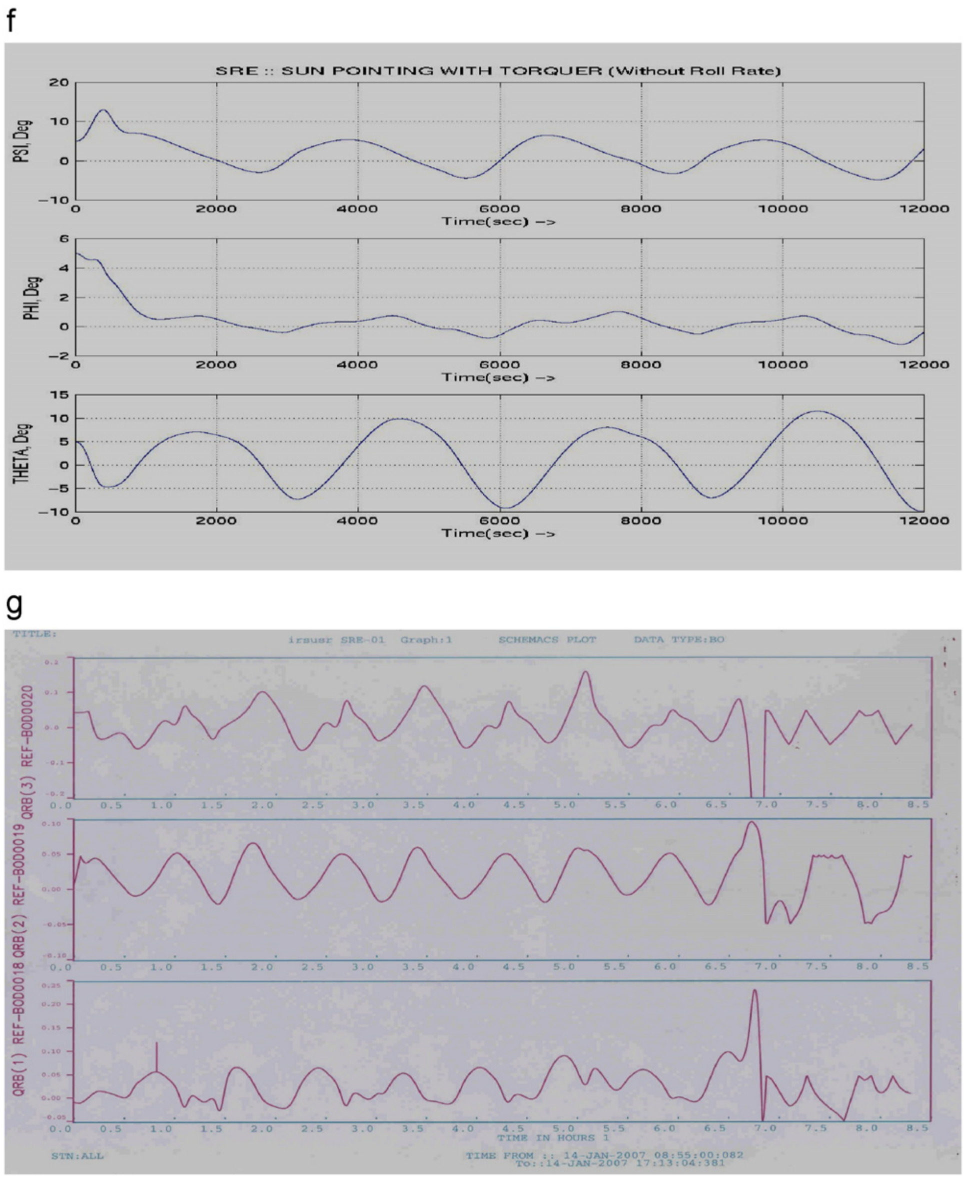


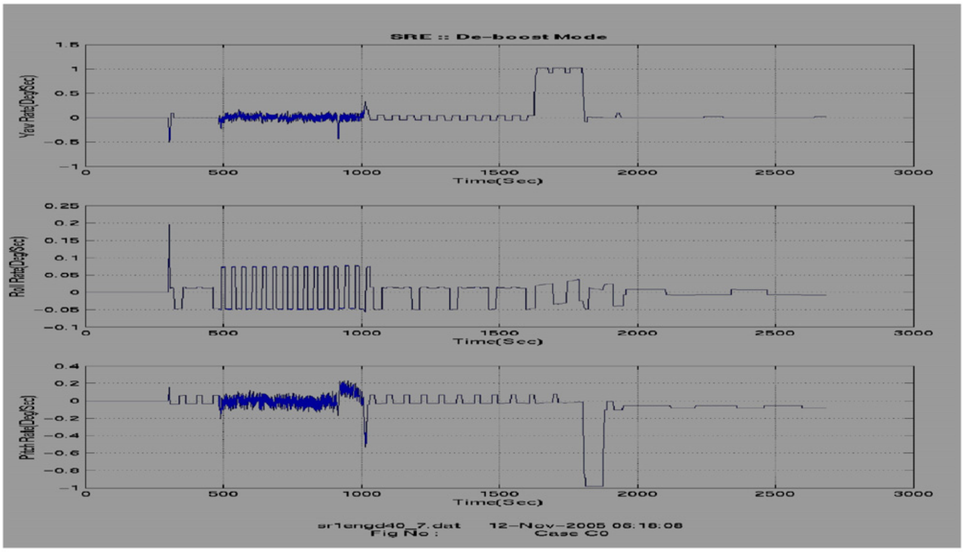

Fig. 8. (*continued*).

delta-$v$, residual disturbance torque will be acting on all the three axes. The off modulation due to this will be of the order of 40–43% depending on the thruster. But if the failure is known in advance, the corresponding opposite side thruster can be put off and the off-modulation can be brought down to about 30%. But in SRE, during the De-boost time ground station visibility will not be available and the failure detection has to be carried out on-board.

During the On-modulation, by enabling both blocks the attitude can be maintained even with single thruster failure without switching off the opposite thruster. But in the case of Open Mode failure, the attitude will be maintained during off-modulation whereas during on-modulation with both blocks, error biases will be developed depending on the thruster which is continuously on. This will result in additional delta V. With single block operation during on-modulation will result in attitude loss with single thruster failure in open mode.

Tables 2 and 3 give the thrusters, the error directions and the actions for its closed mode failure during off-modulation and open mode failure during on-modulation. It can be seen that the error combinations are unique for each thrusters both for open

h

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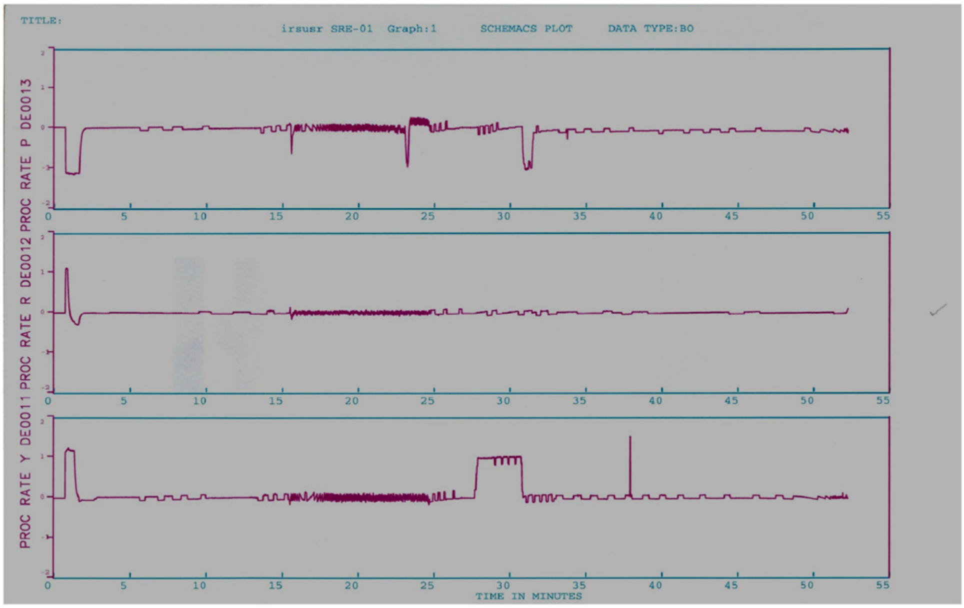


Fig. 8. (*continued*).

mode failure and closed mode failure. Taking these uniqueness properties, the following logic for the failed thruster identification and putting off the opposite thruster and the failed one was studied for the closed mode failure and thruster identification and isolating the block during the coast phase. The error input to the each axis controller is checked for its magnitude and direction and if the error is above a threshold for a selected duration and consistent then the corresponding thrusters will be declared as failed one and the appropriate action will be taken as given in the table. This logic can be used only when both thruster blocks are operational and can detect only one failure.

## 8. Simulation results and performance

The attitude control system design was carried out taking into account the physical parameters, mission

requirements and the actuator capacity. Basically the spacecraft is assumed to be rigid and simulations for the acquisition modes and the on-orbit modes were carried out with the controllers tuned for SRE-1. For de-boost and coasting phases the six-dimensional motion was simulated and the controller design was demonstrated using the program developed for the same.

Typical simulation of error convergence and rate profile during the acquisition phase is given in Fig. 8a and b, respectively. On-board performance of attitude holding with thrusters without roll rate is given in Fig. 8c and Fig. 8d. The rate profile obtained for the case with roll rate is given in Fig. 8e and the rate profile ensured negative yaw towards deep space.

The simulation results for the attitude holding with the magnetic control scheme is given in Fig. 8f and the corresponding on-orbit performance is given in Fig. 8g. It is to be noted that after about 8 hrs, there was an error build up and the automatic switch over to thrusters control was observed. It can be seen that the performance was very good during the holding with magnetic torquer. It is to be noted that attitude control with magnetic controller for a satellite of this size is demonstrated in this mission. For the de-boost and coasting phases, the simulations studies were carried out with the guidance and navigation system and the complete profile of attitude motion which include thrusting, orientation and coasting phases. The attitude rate profile for a nominal case is given in Fig. 8h. The on-orbit rate profile obtained is given in Fig. 8i which is matching with the simulations. The initial high rate in the on-orbit plot is due to the attitude orientation maneuver before the de-boost operations. It is to be noted that, all the eight thrusters were working perfectly and there was no need for a thruster failure detection and re-configuration. During the post flight analysis of the performance, very close match of all the parameters were obtained.

## 9. Conclusions

The control schemes for the different phases of the mission worked perfectly as expected. The magnetic control scheme gave enough confidence for usage of the same for similar class of satellite. The control scheme integrated with the guidance and navigation system demonstrated its perfection.

Overall performance of the SRE-1 control system was excellent.

## References

[1] B.N. Agrawal, R.S. Mcclelland, G. Song, Attitude control of flexible spacecraft using pulse width pulse frequency modulated thrusters, Journal of Space Technology 17 (1) (1997) 15–34.

[2] M.L. Psiaki, Magnetic torquer attitude control via asymptotic periodic linear quadratic regulation, In: Proceedings of AIAA Guidance, Navigation and Control Conference, Denver, Colorado, August 2000 (Paper No. AIAA-2000-4043).

[3] Control Systems Group, Comprehensive Design Review Document for Control System of SRE, Document No. ISRO-ISAC-SRE-RR-0561, ISRO Satellite Centre, Bangalore, September 2006.

[4] Control Systems Group, Control System for SRE—Performance and Analysis, Document No. ISRO-ISAC-SRE-AR-0538, ISRO Satellite Centre, Bangalore, May 2007.